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t: DEVELOPMENT OF SATELLITE INSTRUMENTATION REFERENCE STANDARDS AND CALIBRATION EQUIPMENT FOR MEASUREMENTS AT VERY LOW GAS DENSITIES. initial caps PHASE I REPORT

Prepared under National Aeronautics and Space Administration (NASA) Contract NAS5-14

Phase I ~~Report~~

Jonathan R. Roehrig 24 Oct. 1960 32 p refs

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This report is a presentation of the results of a study of upper atmosphere sensors and calibration methods with recommendations for the construction of an instrument and a calibration facility. Since the study covers two distinctly separate problems, the report will be divided in the same manner. The investigation of the low gas density sensor will be considered first followed by the study of calibration methods.

Each of these studies began with a review of the literature. These reviews provided an initial screening of presently available methods as well as an indication of some of the problems of the more sophisticated methods presently in the experimental stage. After the initial survey the more promising approaches were studied in detail along with new ideas generated from discussion sessions within National Research. From this information, final recommendations were developed to complete the study.

High Altitude Sensor

In order to obtain the best results from a study of this kind, it is necessary to work out the areas of interest and put limits on the problem. The basic starting point is the desire to determine the structure of the upper atmosphere of the earth. In the past ten years, much information has been obtained at altitudes up to 200 miles with conventional measuring techniques, but as rocket flights have been reaching higher and higher altitudes, these instruments have reached the limits of

their sensitivities. Other instruments must be found to make the desired measurements. Although there are many physical measurements that will be required in order to completely understand the atmosphere, we are here concerned with measuring the molecular density and molecular species of the gases that are found above 200 miles. Other areas of interest are measurements which may be interrelated with these, such as electron density and ion densities and kinetic energies of the various component gases.

Measurements of these quantities have been made at lower altitudes, to obtain information at higher altitudes will require more sophisticated instrumentation. This increases the reliability problem and the time required to reduce the data.

Although it is undesirable to confine the study within too narrow limits at the beginning, consideration of factors related to the vehicle and environment must be kept in mind in order to quickly determine general suitability of new approaches to the problem. Size, weight, and reliability are, of course, primary considerations. However, wide dynamic range and fast dynamic response to the quantity being measured, relatively unaffected by other environmental factors, are also required since the vehicle will traverse large changes in densities and environment at very high speeds. Each of these considerations is not in

itself a limiting quantity since some compromises can be made; some very desirable features may outweigh some of the disadvantages.

The study of sensors was initiated with a detailed review of the literature. This included sensors for measuring densities of gases at low pressure (primarily vacuum gauges) and methods for gas analysis. Substantially all of the published work in atmospheric research was also covered. Two project reports (Technical Reports #1 and #2) have been issued reviewing the literature in the fields of vacuum gauges and mass spectrometers, these being the best known of the possible sensing devices. Some of the instruments listed can be quickly removed from consideration due to basic limitations, but there are many which must be considered in detail. The following paragraphs will discuss the more interesting devices.

Since the pressure range of interest extends to 10^{-12} mm Hg, most vacuum pressure gauges can be eliminated from consideration as satellite sensors because the physical principle on which they operate is not useful at the lower end of the range. However, some of these gauges with limited range may still be interesting for calibration purposes. The gauges which are not likely to be useful at 10^{-12} mm Hg include the Pirani, thermocouple, radiometer, Bourdon tube, diaphragm, and McLeod gauges.

Pirani and thermocouple gauges depend on the thermal conductivity of a gas. The thermal conductivity is pressure dependent primarily in the range from one micron to one mm Hg. High sensitivity instrumentation has been used to extend the range to about 10^{-5} mm Hg but below this value there are not enough molecules striking the hot filament to conduct a measurable amount of heat. Other heat losses obscure any detectable variation in the thermal conductivity of the gas.

The Knudsen radiometer gauge is limited to the pressure range 10^{-5} to 10^{-8} or possibly 10^{-9} mm Hg. This limit is established by the lowest force presently measurable on the cold vane. If smaller forces could be measured, an ultimate limit is set by the point at which the magnitude of the molecular pressure on the cold vane becomes comparable to the radiation pressure.

Bourdon tubes and diaphragm gauges are also in this class although the factors limiting the presently available ranges are primarily due to structural materials and measurement limitations rather than limits in basic principle. This is true for most of the instruments that depend on measuring a force. If better materials were available for the construction of the tube or diaphragm, and more sensitive measurements of the deflection could be made, the range could be increased.

Sorbed gas on the interior surfaces of the McLeod gauge limits its use to pressures above 10^{-7} mm Hg. Mechanical and operating factors limit practical gauges to pressures above 10^{-5} mm Hg. A detailed discussion of the McLeod gauge is given in Technical Report No. 3 and it will be further considered in the calibration section of this report.

Another class of gauges, which includes most of the popular methods for measuring pressures below 10^{-3} mm Hg, measures the number of molecules in a given volume and hence these are density gauges. This class includes the various hot-and cold-cathode ion gauges. A recent report [1] provides a thorough discussion of this group of instruments. For this reason only the problems related to the measurements of the upper atmosphere will be discussed here.

The basic operating principle is the ionization of the gas in a defined volume. The ions are collected and the resulting current is a measure of the total number of gas

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1 Final Report under Contract AF 19(604) - 5731, sponsored by AF Cambridge Research Center; National Research Corporation, Cambridge, (February, 1960).

molecules in the defined volume. It would appear from this statement of principle that the gauge could serve as an absolute standard. By an absolute standard we mean a gauge whose response can be accurately predicted solely on the basis of its physical dimensions and on known physical laws, without need for calibration. However, the ionization process cannot be defined with enough precision to provide a satisfactory standard. The factors influencing the ion current I_i can be indicated in the formula:

$$I_i = NKLD \qquad (1)$$

where N = number of ionizing particles per second (electrons, alpha particles, etc.), K = number of ions formed per unit path length at a given gas density, L = average path length of an ionizing particle, and D = gas density.

The number of ionizing particles can be well defined by measuring the electron current or from known disintegration rates of radionucleides. Factor K, however, is known only approximately; its value depends on the kind of ionizing particle, its energy, and the kind of gas molecule being ionized. Further, values of K cannot yet be accurately predicted on theoretical grounds alone, and are determined experimentally in apparatus similar to an ion gauge. The average path length, because the ionizing volume is not

sharply defined by the electrode structure, is probably the factor hardest to determine in the usual configuration. It is possible to construct the gauge so that the path length can be determined accurately but the sensitivity will be lower.

However, if we consider calibrating the gauge with a standard and then using it to measure the upper atmosphere, the major problem is its dependence on gas composition. Since the ionization probability (K) varies over a wide range for different gasses, and if the atmosphere to be measured is not a pure gas but a mixture, the true mean density cannot be determined unless the composition is known. This dependence somewhat reduces the usefulness of an ionization type gauge for upper atmosphere research, although if the density is known it can give the average molecular weight of the gas. However, a mass spectrometer can provide an analysis of the composition from which the average density can be determined, as well as the total gas density.

If the atmosphere to be measured is already partially ionized, the collection of these ions will add to the current generated by the ionizing source in the gauge. An ion trap at the entrance to the gauge can prevent the ambient ions from entering the gauge, and the gauge will then indicate only the

partial pressure due to the un-ionized molecules. The gauge must be shielded against outside sources of ionizing radiation for the same reason.

The problem of adsorption and desorption of gasses on the walls of the gauge or on the internal elements is present in any low pressure sensing device. The true density can only be determined when these processes are in equilibrium with the surrounding atmosphere. During large and rapid excursions of the density, the gauge reading will lag the true density. If the density is increasing the gauge will read low because the internal surfaces act like a pump, adsorbing the incoming gas. If the density is decreasing, the surfaces will outgas resulting in a higher density in the gauge. Similar behavior is observed following rapid changes in temperature, because the sticking probability is a function of temperature. This phenomenon is well known to users of hot filament ion gauges.

The surface equilibrium can also be affected by the bombardment of a surface with ions or electrons. This effect can be observed when a cold cathode gauge is first turned on. The pressure reading, initially high because adsorbed gas is dislodged by bombardment, will gradually decrease until equilibrium is attained. In a hot filament gauge, the effect is obscured by the much larger outgassing due to the sudden

temprature rise when the filament is turned on.

The calibration stability of an ion gauge is usually excellent. The physical parameters affecting the ion current (Eq. 1) are stable or can be controlled. The number of ionizing particles per second is determined by the electron current. If the electron current is measured, the ratio of ion current to electron current is proportional to density. If the electron current is maintained at a constant value, the ion current is proportional to density. The average path length is fixed by the dimensions of the elements and their spacing. If in the hot filament gauge the accelerating voltage is maintained constant, the energy dependence of the factor K will be stabilized. Since these are the parameters which determine the ion current, stability is maintained over long periods of time.

Miniaturizing and ruggedizing the ion gauge presents some not insurmountable problems. Physically the sensing element itself can be reduced to a very small size (subminature vacuum tube). However, since the value of the path length, L is directly proportional to the physical dimensions, the ion current will be reduced accordingly. Therefore, minaturizing must compromise between size and lowest detectable density. The cold cathode types of ion gauge require a magnet whose size and weight are not easily reduced to small values. While the weight is a distinct

disadvantage, it is not so large as to disqualify the gauge from consideration.

Providing the capability to withstand high shock and vibration forces presents a problem only in the hot filament type of ion gauge. Here the requirement for strength is opposed to the requirement for low power consumption. However, since hot filament vacuum tubes have been designed to withstand these forces, the technology is available to overcome the problem. The cold cathode and radioactive source gauges present no difficulties; good design with proper supports for the internal structure is all that is necessary.

The ion gauges in one form or another have been the accepted instrument for measuring pressures in the range of interest of this study. The conventional hot filament ion gauge is limited to pressures higher than 10^{-8} mm Hg by the X-Ray effect. The Bayard-Alpert modification reduces the X-Ray effect so that the limit is extended to 10^{-11} mm Hg. Some non-linearities have been observed in the Redhead cold cathode gauge in the 10^{-12} mm Hg range.

The low pressure limits of these gauges can be extended by several orders of magnitude by the flash filament technique. This method does not improve the characteristics of the gauge

itself, but in fact, multiplies the pressure to be measured for a short period of time. The principle is as follows: A clean surface will adsorb gasses at a fairly constant rate (as long as the coverage is less than a monolayer of gas). If the surface is then heated to a high temperature, the adsorbed gas will be quickly desorbed. If this occurs in the vicinity of an ion gauge, the gauge will read the pressure "burst". The peak reading of the gauge is related to the initial gas pressure and the length of the adsorption period. A thorough analysis of this technique is presented and discussed in the previously mentioned report (see page 5). However, several considerations related to possible uses of the method in a satellite sensor should be discussed.

In order to obtain the maximum gain in sensitivity, the surface area should be as large as possible. On the other hand, the power required to heat the surface increases with the surface area. While the average power is not large because of the short duty cycle, peak power requirements must also be considered.

To obtain the full advantages of the method over a wide range in total pressure, the duration of the adsorption period should be variable. This could be accomplished in a number of

ways but requires additional circuitry for self-sensing or a command link with the ground. For a fixed adsorption time, the dynamic range of a particular gauge is at least 100:1, which should be sufficient for many satellite applications.

Because a finite time period is required for adsorption, the measurement will be an average of the pressure experienced over the period. The fast-changing pressure experienced by a rocket fired vertically upward through the atmosphere could not be satisfactorily measured by this method. However, for investigations beyond the earth's atmosphere where changes in the density are expected to be much more gradual, the information obtained would be very useful.

The tubulation between the gauge and the atmosphere is a critical factor in the design of the instrument since it limits the pumping speed in both directions. With a large opening, the rate of adsorption is controlled by the sticking probabilities of the molecules on the clean surface. During the desorption cycle, the pressure burst will be quickly pumped out to the surrounding atmosphere; this will require a fast response of the amplifier if the reading is to be useful. With a small opening on the other hand, the rate of adsorption will be limited by the conductance of the tubulation and longer adsorption times will be required. On desorption, the pressure burst will be pumped out

more slowly. For these reasons the sensor must be calibrated with the proper conductance.

A further consideration in the design is the thermal energy introduced by the hot filament. The heating cycle must be as short as possible in order that the walls of the gauge do not change in temperature. Such a temperature increase would release adsorbed gas from the wall, which would interfere with the pressure measurement.

Although the finite adsorption time required may be a disadvantage in most applications, the method can increase the range of any ultra-low pressure measuring instrument. The simplicity with which this is accomplished would seem to deserve thorough consideration.

Mass Spectrometers

A number of mass spectrometers have been flown in rockets and in at least one satellite. For the most part, these have been Bennett type instruments, although several other types are being constructed for future flights. Since most of these instruments have been described in Technical Report Number 2, and the principles are fairly well known, a general review will not be undertaken here. A well-designed instrument will measure partial pressures in the 10^{-8} to 10^{-9} mm Hg region with the usual

DC amplifier for measuring the ion current. With more sophisticated current measuring techniques the pressure limit can be extended one or two orders of magnitude. Further improvements to permit measuring still lower pressures may be possible through a study of the several processes involved.

The functional operation of the usual instrument can be divided into three distinct processes: ionization, separation, and a physical measurement of each group of ions. The output-input specifications imposed on each stage differ widely among the various types so that the details of the physical arrangements are different, but the basic processes are the same in each case. An understanding of the relationship that each process has with the sensitivity can best be obtained if the discussion starts with the final measurement. In almost all cases, this is a measurement of the ion current and in every case is the factor limiting the lowest pressure detectable by the gauge. In other words, the ion currents exist but are below the threshold of present current measurement techniques. If we assume a minimum measurable current, then the sensitivity can only be increased by increasing the number of collected ions which form the current. This attack points to two factors: the number of ions formed, and the ion utilization efficiency.

The ion efficiency of the system, the relationship between the number of ions collected to the original number of ions

formed, is a function of the efficiency with which the ion source injects the ions into the analyser, the loss of ions in the analyser, and the collection efficiency at the output of the analyser. With good resolution by the analyser, and proper design of the collector the collection efficiency should be nearly 100%. The other two factors are related to each other: The analysers with high ion efficiency require an ion source with a collimated beam, while those analysers that can use an ion source without collimation have high losses. For example, in the Bennett type M.S. essentially all of the ions formed in the source are injected into the analyser, but the accelerating grids will, themselves, collect many of the ions before they can reach the collector. On the other hand, an analyser of the crossed field type which has very low ion losses requires a source that can usefully deliver as a collimated beam only a small fraction of the number of ions formed. In the time-of-flight instrument, where the ion source is pulsed, the low ion utilization efficiency arises from the short duty cycle. From this, it can be seen that, in almost every case, the dominant factor in ion efficiency is the losses at a single point and for most spectrometers, this point is the ion source.

The function of the source is to ionize the gas and inject the ions into the analyser. The specifications for the ion beam vary quite widely, but in general require a colimated beam of ions

all at approximately the same velocity. The losses are primarily the result of forming the beam. The "brute force" method of extracting the ions through a hole in a box is the most common method; most of the ions collected on the walls of the box. It would appear that a much more efficient method could be developed through the application of the principles of electron optics. An efficient ion gun would be useful in many applications.

Another possibility for improving the lower pressure limit by increasing the sensitivity is to increase the number of ions formed. The obvious step is to increase the number of ionizing electrons. However, several factors in the design limit the electron current. The beam forming method limits the volume from which the ions are extracted, so that only the electrons passing through the volume produce useable ions. The usual "brute force" method for producing the electron beam requires introducing the electrons through a second hole in the box, and thus also limits the electron current. Although other factors such as space charge and electron energy must also be considered, there is the possibility for great improvement in the ionization section of the mass spectrometer.

Many of the vacuum problems discussed previously in connection with the ion gauge also apply to measurements with the mass spectrometer.

As in the ion gauge, if the atmosphere to be measured is partially ionized, the data cannot be unambiguously interpreted. The use of an ion trap is indicated and the measurements are then related to the unionized molecules. The mass spectrometer can be used to measure only the ionized molecules by removing the ion source and permitting the ambient ions to enter the analyser. Ions of either polarities of the accelerating voltages must be reversed for ions of different polarity.

A survey of the literature indicates that there is much activity at the present time in the development of mass spectrometers for upper atmosphere research. Many of the various types of M.S. are under intensive investigation and will be constructed as flyable instruments. Another instrument which is not a true mass spectrometer but can provide similar information is known as the desorption spectrometer. This device has so far received little attention, but appears to offer distinct advantages. It therefore deserves further consideration of its potential capabilities.

Desorption Spectrometer

The desorption spectrometer is a method for the analysis of extremely low pressure gas mixtures that has so far been given little attention. Although the physical phenomenon has been known

for some time, it has only recently been applied to measurements in ultrahigh vacuum systems. The desorption spectrometer is an extension of the flash filament technique. A clean filament is used to adsorb the gas but instead of desorbing all the gas in a short time, the filament is heated slowly. Since different gasses desorb at different temperatures, because of their different binding energies, a pressure burst is indicated by the ion gauge for each of the adsorbed gasses. Althought the extent to which good resolution is possible among the various gasses is not known, the technique is useful at pressures much lower than any other known method.

The instrument is not a mass spectrometer, and the recorded spectrum is in no way related to a true mass spectrum. The peaks obtained depend not only on the binding energy but also on the time period of adsorption, the sticking probabilities, the flow characteristics of the instrument envelope, and the composition sensitivity of the detecting pressure gauge. Because some of these factors are not well known, each instrument must be individually calibrated.

Most of the current work in desorption spectrometry is being carried out by P. A. Redhead of the National Research Council of Canada in Ottawa. This work has developed excellent data on the desorption characteristics for nitrogen, carbon monoxide, and

hydrogen sorbed by a tungsten filament. Some of the problems involved are also pointed out by these experiments.

Some of the gasses do not have a single desorption peak. This may be due to several causes. The tungsten filament has a multicrystalline structure with random orientation of the crystals so that all of the various crystal faces are exposed. Each of the crystal faces may adsorb the gas molecules with somewhat different binding energies. The gasses on the several crystal faces will, therefore, desorb at different temperatures. Further, the individual gas molecule may be bound to a single metal atom or to more than one metal atom. This also leads to desorption at different temperatures. These results are based entirely on the desorption from tungsten. Other materials for the filament may have entirely different characteristics. It may be possible to find a different filament material that will alleviate some of these problems.

The flash filament technique itself would also appear to be useful as a method for extending the sensitivity of a mass spectrometer. As far as is known, the combination has never been used. The resulting mass spectrum would not be directly related to the gas composition but would depend on the adsorption characteristics of the flash filament and the gas dynamics of the system. However, the added sensitivity (possibly two orders of

magnitude) would be very useful and balance the added calibration problems.

Recommendation

The previous paragraphs have discussed in detail a number of sensors for high altitude measurements, their advantages and disadvantages. In order to avoid duplication of effort, a review of the investigations in progress at the present time should be considered before a final recommendation for the construction of an instrument is made.

The development and construction of several ultrahigh vacuum gauges as flyable instruments is now underway. At NRC Equipment Corporation (a subsidiary of National Research Corporation) work is proceeding on the Redhead cold cathode gauge. This project should be completed in the near future. Under intensive investigation for use in rockets and satellites are the Bennett MS, the omegatron, the Bendix T.O.F., the Paul "Massenfilter", and the crossed-field M.S. by various groups including NASA, Itek, University of Michigan Research Institute, Consolidated Systems Corporation, Lockheed Aircraft, Bendix Aviation, and Naval Research Laboratory, as well as institutes in Russia.

Because of this work already in progress, which covers the pressure range of interest in this program, the development of a sensor for altitudes beyond this range would probably contribute

more to high altitude research. This study, therefore, recommends the further experimental investigation of the desorption spectrometer and the development of a high altitude sensor based on the principle.

Calibration Facility

The second part of Phase I is the study of methods for calibrating high altitude sensors with recommendations for the design and construction of a calibration facility. This study was begun with a review of the literature, which has been reported in Technical Report #1. A further detailed study of the McLeod gauge and the Knudsen gauge is the subject of Technical Report #3.

Many of the low pressure sensors can be calibrated directly over their whole range with the McLeod gauge. With careful construction and good technique the method can be useful, to pressures low as 10^{-5} mm Hg with reasonable accuracy. The calibration of instruments below this range is primarily by extrapolation of the calibration made at the higher pressures. The ion gauges, in particular, have a linear relation between the ion current and density so that, in theory at least, calibration by extrapolation to lower pressures works quite well. However, in practice, other physical phenomena can and do affect the calibration at lower pressure. The standard ion gauge is limited by the X-ray effect

which adds to the ion current. At pressures below 10^{-7} mm Hg the ion current begins to level off and a constant reading in the 10^{-8} mm Hg range will be indicated no matter how much lower the pressure actually is. The Bayard-Alpert modification reduces the point at which the effect limits the ion current but this gauge still has an X-ray limit at about 10^{-11} mm Hg. The inverted magnetron gauge of Redhead also exhibits a non-linearity at 10^{-12} mm Hg and below. For these reasons, calibration by extrapolation below a measured point is not a reliable method.

Extension of the lower range of the McLeod gauge, at least by orders of magnitude, does not appear to be a reasonable expectation. The Knudsen gauge may be regarded as a standard to approximately 10^{-9} mm Hg below this pressure no absolute standard is known.

The calibration problem can be attacked from another direction. Instead of directly comparing the known and unknown gauges, a "known" low pressure can be obtained by expanding a known volume of gas to a larger known volume and applying the gas law $\frac{PV}{T} = \frac{PV}{T}$. This method has been used at higher pressures as an independent check on other standard instruments. However, as the pressures is reduced a number of inaccuracies appear. Of these sorption and desorption on the walls of the vessel are probably the major problem. As the pressure is reduced the quantity of gas adsorbed on the walls

becomes an appreciable part of the total gas in the system. A small volume of gas expanded into a large chamber will not follow the gas law since part of the gas will be adsorbed. Other problems associated with this static system are the pumping action of ion gauges, outgassing of seals and valve gaskets, and the cumulative effect of these errors if more than one expansion is required. For pressures below 10^{-3} or 10^{-4} mm Hg these sources of error become a dominant factor of the true pressure and render the method useless.

Many of the problems can be overcome by using a dynamic system as the pressure division system outlined in Technical Report #1. By pumping continuously thru a small orifice from a chamber at constant pressure, a new lower pressure can be achieved whose value depends only on the conductance of the orifice and the pumping speed. If the pumping speed is large compared to the outgassing rates and gauge pumping rates, these will not affect the accurate determination of the new pressures. Sorption and desorption are not a problem since the walls of each chamber are always maintained at one or within a small range of pressures.

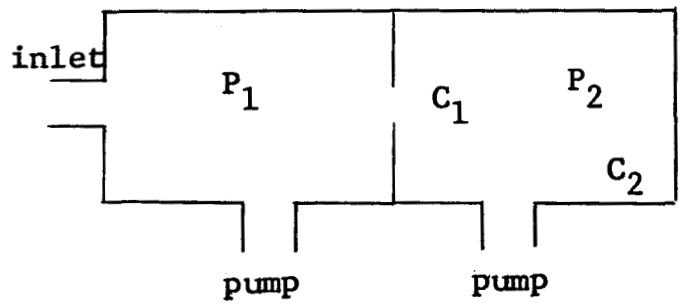


Figure 1

The basic outline of the system is shown in Figure 1 where $(P_1 - P_2)C_1 = P_2 C_2$. C_1 is the conductance of the orifice and C_2 is the effective pumping speed. The pumping system includes a second orifice which limits the effective pumping speed to a value well below the inherent speed of the pump so that the pressure ratio is determined primarily by the ratio of the orifice conductances, with little effect from variations in pump speed. The constancy of the conductance of an orifice should lead to a very stable value of the pressure ratio.

This would appear to be an ideal pressure standard which can be extended to very low pressures. In order to obtain a true value of pressure ratio the chambers must meet a number of requirements. The leak and outgassing rates must be negligible compared to the desired gas flow: With the connecting orifice closed, the chamber must attain a pressure 100 times lower than the normal operating pressure if 1% accuracy is required. The gas flow through the pump must be large compared to the pumping of any gauge attached to the chamber. The pressures must be in the region of molecular flow, in order that the orifice conductance remains constant. For this reason, the molecular beam from the orifice must be dispersed, otherwise, the pressure distribution throughout the chamber will be uneven.

The requirements for molecular flow removes the possibility of using atmospheric pressure as the reference. However, a standard pressure measurement can be made at 1 micron pressure with the McLeod gauge. In this range, the McLeod is free of many of the troubles found at lower pressures. Starting with 1 micron, and assuming a pressure division of 100 as reasonable, four successive chambers with orifices and pumps can be used to reach a pressure of 10^{-9} mm Hg which will be directly related to the 1 micron pressure as shown in Figure 2.

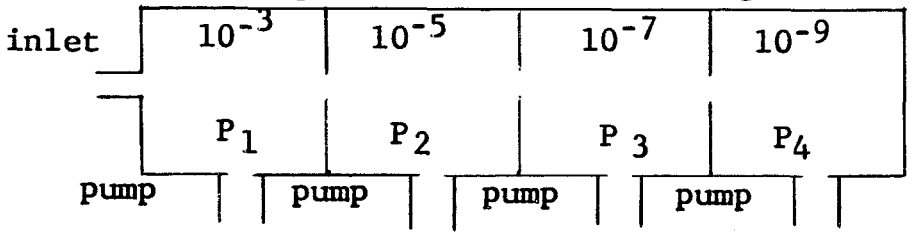


Figure 2

In this manner a gauge mounted on the final chamber can be calibrated by a determination of the pressure in the initial chamber with the McLeod gauge. The pressure in the final chamber can be varied over several ranges by valving the pumps in the intermediate chambers and still maintain a known relationship with the primary pressure.

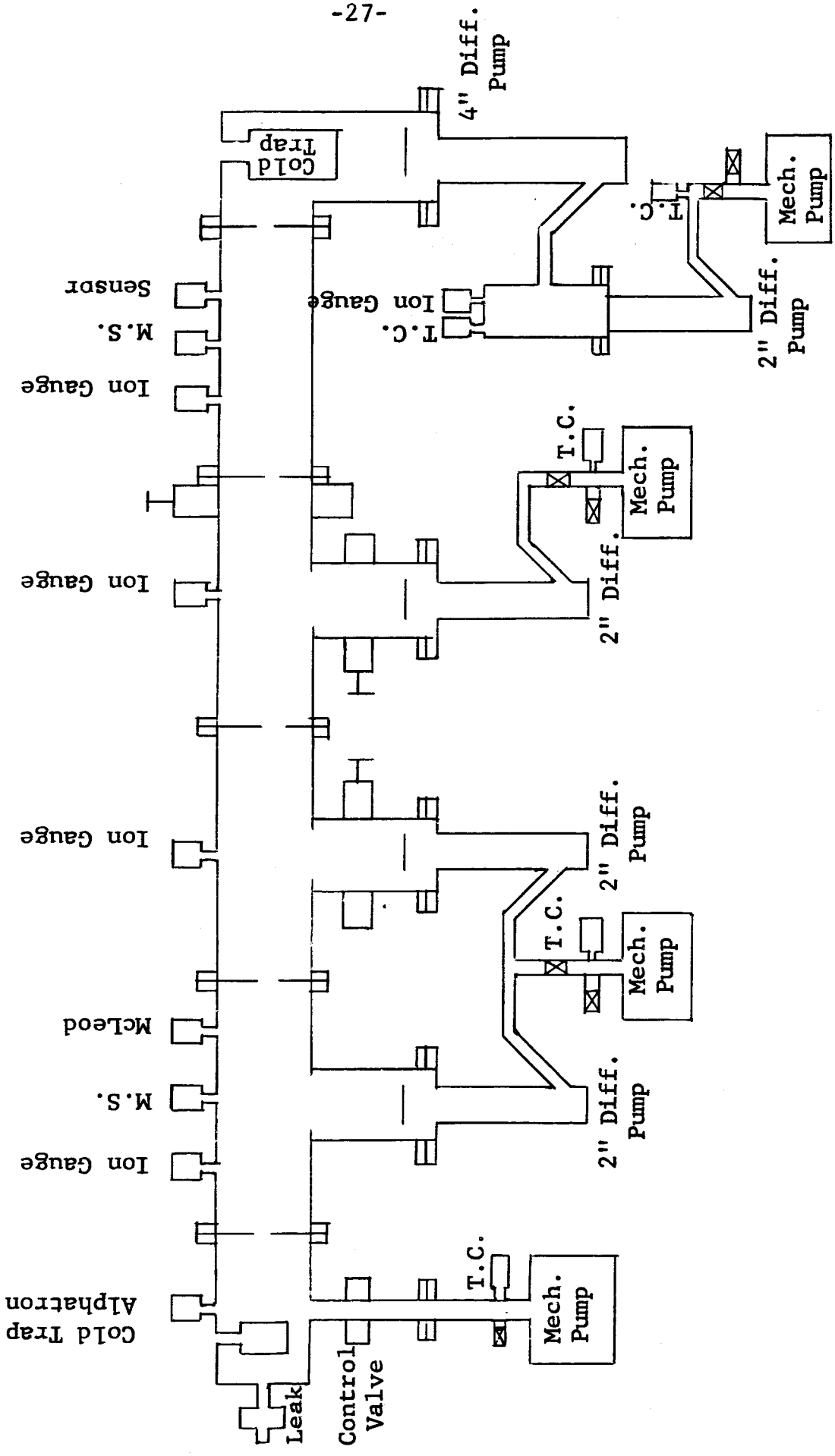
This principle may be theoretically extended to lower pressures by adding another pumped chamber and orifice. With glass systems, sealed and pumped with the ion gauge, pressures in the 10^{-12} mm Hg range have been attained. This type of chamber could be added to extend the calibration pressure to about 10^{-10} mm Hg; with the required high ratio of operating pressure to blank-off pressure, this pressure is about the limit of today's technology

However, when better techniques to obtain lower pressures are discovered, calibration at lower pressures will be possible by this method.

Since this approach to a calibration system appears to have many advantages, an initial design was laid out in order to study the concept from an engineering standpoint. This design is shown in Figure 3. A series of five chambers are connected by orifices. In each succeeding chamber, the pressure is a factor of 100 lower than in the preceeding chamber and the useful ultimate final pressure is 10^{-9} mm Hg.

For calibrating a sensing device over several decades it will be unnecessary to move the gauge from one chamber to another since, by selectively closing the valves to the pumps in the third and fourth chambers, the pressure in the final chamber can be increased by orders of magnitude and still provide a known pressure.

1. The first chamber is essentially a stabilizing volume. An inlet is provided for admitting either atmospheric air, a pure gas, or a known mixture of gases. A cold trap is provided for freezing out condensibles. This chamber is pumped with a mechanical pump and is maintained at approximately 100 microns pressure. The actual pressure can be maintained at a constant level by a feedback system


Cold Trap Alphatron
M.S.
McLeod
Ion Gauge
M.S.
Ion Gauge
Ion Gauge
Ion Gauge
Sensor
Cold Trap
4" Diff. Pump
T.C.
Ion Gauge
T.C.
2" Diff. Pump
Mech. Pump
T.C.
2" Diff. Pump
Mech. Pump
T.C.
2" Diff. Pump
Mech. Pump
T.C.
Mech. Pump
Leak
Control Valve

including an Alphatron gauge which operates a valve on the pump inlet. The pressure can be selected by adjustment of the Alphatron circuit. This chamber is connected to No. 2 chamber by an orifice.

2. The basic pressure measurement is made in this chamber with a McLeod gauge. The pressure is controlled by the pressure in chamber No. 1, the orifice between the chambers, and the orifice at the pump. The pressure can be controlled over the 10^{-3} mm Hg range by adjusting the set point of the Alphatron on chamber No. 1. The 2" diffusion pump is provided with a trap to prevent the migration of pump fluid vapor to the chamber. Baffles are included to prevent beaming of the incoming gas and to reduce the possibility of non-uniform pressure distribution within the chamber volume. Instrumentation will include (1) a modified ion gauge to provide basic calibration for the succeeding ion gauges with gases other than air, (2) a mass spectrometer to provide basic data on the composition of the incoming atmosphere, and (3) the primary standard McLeod gauge.

3,4. The succeeding two chambers are identical and merely provide the stable pressure divisions necessary to arrive at a pressure of 10^{-9} mm Hg in the fourth chamber. Each includes the orifice connection and a 2" diffusion pump with trap and valve. The only instrumentation is an ion gauge for maintaining a constant check on the performance of the system. Baffles are again a part of the internal structure.

5. The final chamber is the operating point for the gauge to be calibrated. A number of openings are provided for attaching the gauge either by a metal-to-glass seal or by heliarc welding. An ion gauge and mass spectrometer are included for the final check on pressure and composition. A 4" pump with trap and orifice are also attached. The fore pumping system includes a 2" diffusion pump and mechanical backing pump with gauges for foreline monitoring. This and the preceding chamber are provided with an insulating enclosure for baking - a necessary procedure to obtain the final low pressure. A valve must also be included in the orifice connection with the preceding chamber

for isolating this chamber when the gauges are mounted or dismounted.

The series of four ion gauges (either the Bayard-Alpert or Nottingham modification of the standard gauge) may be operated from a single control box and the two mass spectrometers may also use common electronic components. A fast-sweep type of mass spectrometer is preferred since its use is primarily for comparison purposes and as a check on the air-tight integrity of the system.

The system must be constructed of stainless steel. While it would be reasonable to feel that this is not necessary for the higher pressure chambers, any change in outgassing characteristics of the surfaces is undesirable. The surface of a mild steel wall will rust over a period of time and the outgassing rate will change considerably. Although outgassing in the usual sense is not a problem because this part of the system is not exposed to the atmosphere, a porous surface (due to rust) will require long periods of time to reach equilibrium when the composition of the atmosphere is changed.

In order to maintain outgassing in the low pressure chambers, rubber gaskets and seals must be kept to a minimum. This will require very careful design in order that the chamber will still be accessible for cleaning. In the final chamber, all

gasketed joints must be cooled for baking and to reduce outgassing during operation.

If the theoretical basis for pressure division is to be maintained, every possible precaution must be taken to minimize leaks and outgassing in the final chamber. If 1% accuracy is desired, the gas flow due to these sources must be 1% or less of the desired flow through the orifice. Therefore, it must be possible to pump chamber #4 to 10^{-9} mm Hg and the final chamber to 10^{-11} mm Hg.

The use of refrigerated (liquid nitrogen) traps to prevent the migration of pump oil into the system is standard practice in ultrahigh vacuum technology. Some experiments have been reported using non-refrigerated traps with zeolite or alumina. This kind of trap would be very useful for this system not only from a cost standpoint but for standby operation. During periods when the system is not actively in use, the chambers should be maintained at low pressures. If the cold traps are not used during these periods the oil can migrate into the clean system. Reported experience indicates a very long life for the non-refrigerated traps without attention. For this reason the use of this type of trap for each diffusion pump in the system would be very desirable.

From an engineering standpoint, all the specifications and requirements discussed above can be met with the exception of the pressure of 10^{-11} mm Hg for the final chamber. This low pressure has not been attained in metal systems as far as is known. However, by applying the knowledge gained from past experience with larger chambers pumped to 10^{-10} mm Hg, it should be possible to attain a pressure in the low 10^{-11} region in this small chamber. If a pressure of 3×10^{-11} is attained, the measurement accuracy at 3×10^{-9} will be 1% and at 1×10^{-9} it will be 3%.

This concept for a calibration method meets the requirements of the problem and its execution in physical hardware does not appear to have major difficulties. For this reason, it is the recommendation of the study to design and construct a calibration facility using this approach.